National Aeronautics and
Space Administration
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

TPF Terrestrial Planet Finder Interferometer

TPF-I Mid-IR Interferometry Technology

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Exoplanet Science and Technology Fair

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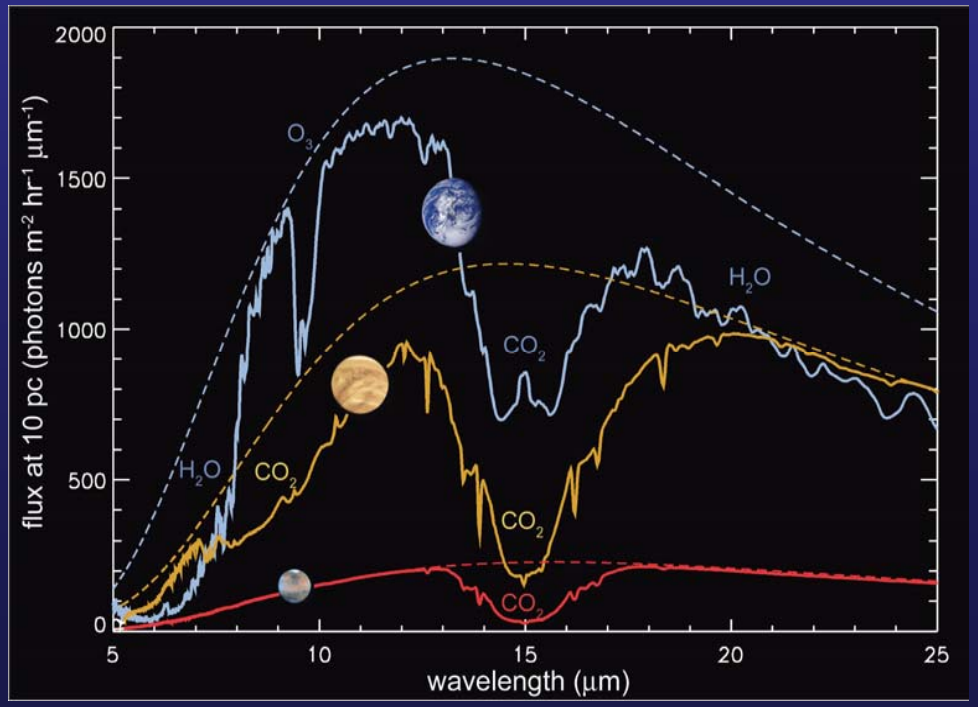
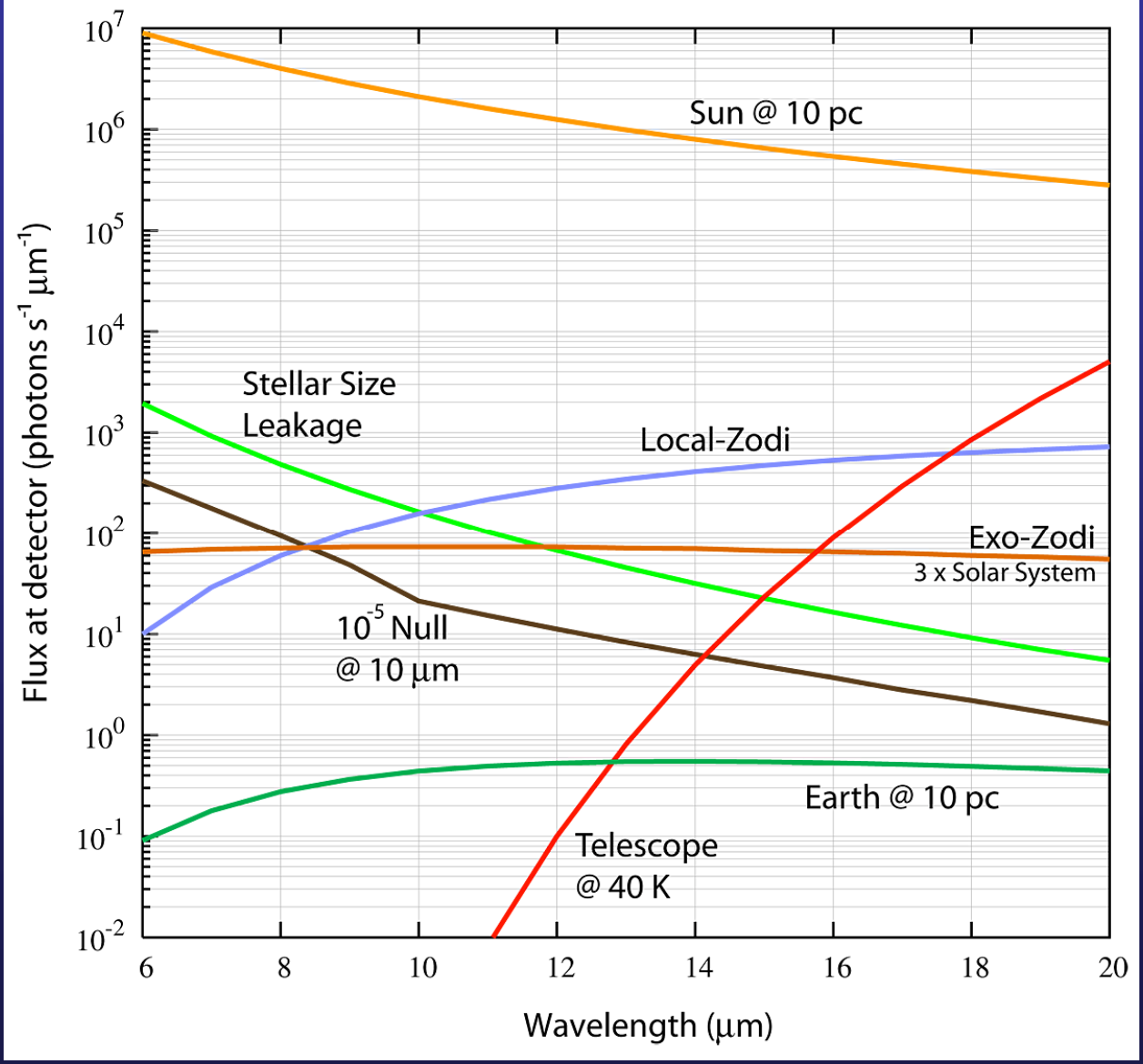
Key Features

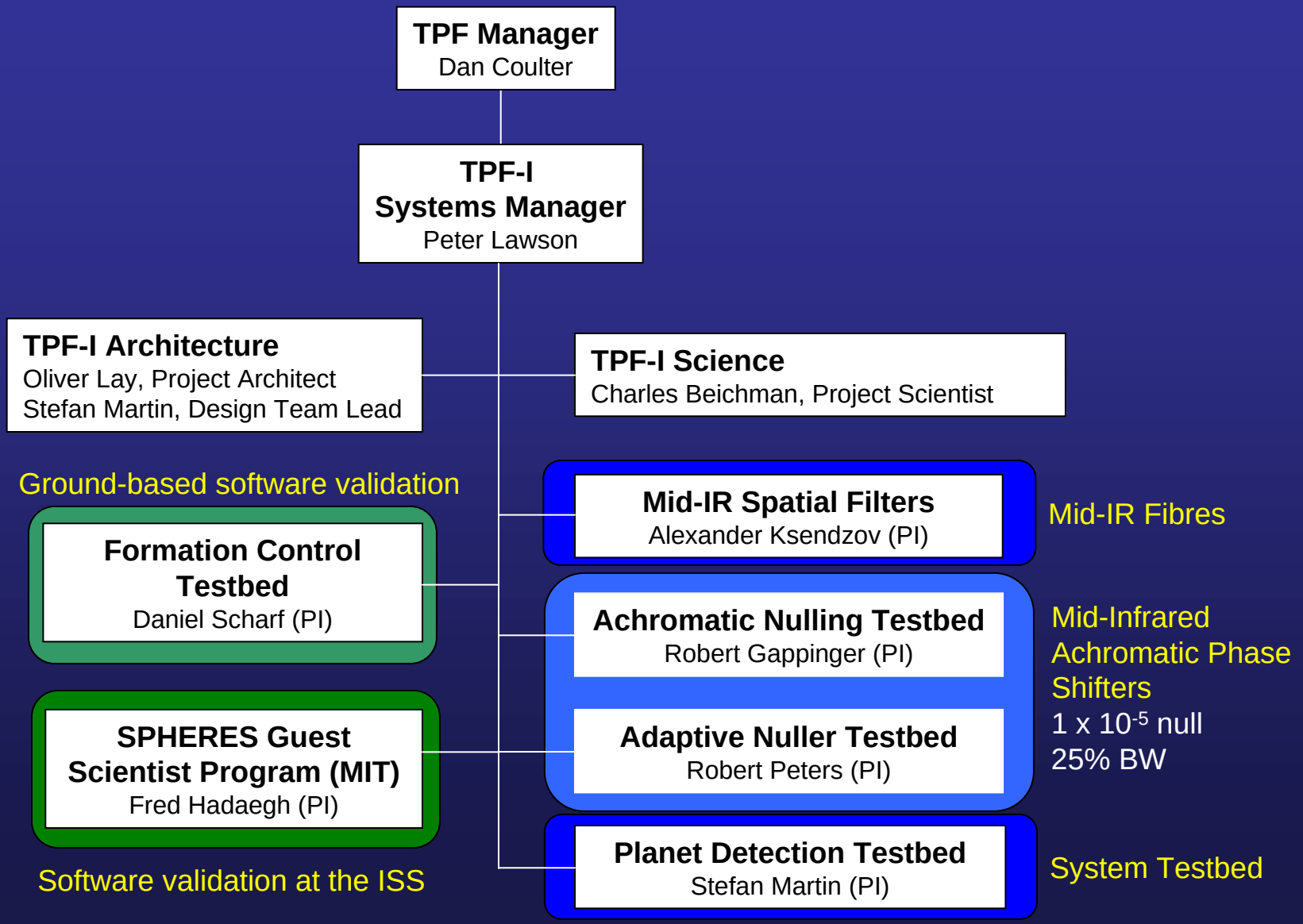
- **Wavelengths**: Mid-Infrared 6 – 20 μm
- **Contrast**: Earth-Sun ~ 10^7 @ 10 μm
- **Biomarkers**: O_3, CO_2, CH_4, H_2O
- **Technique**: Nulling Interferometry
- **Implementation**: Formation Flying



Sources of Noise at Mid-Infrared Wavelengths

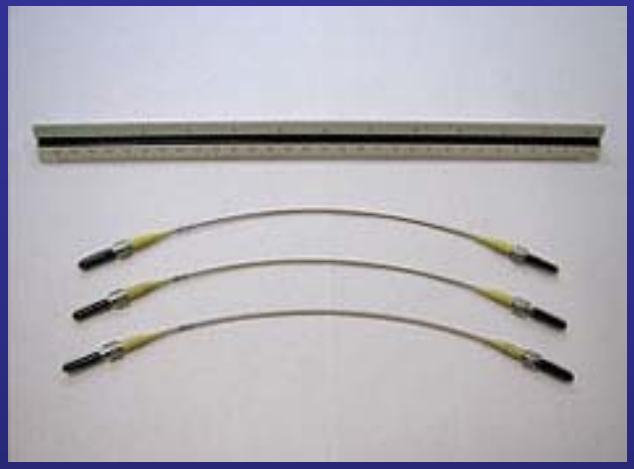


TPF-I Organization & Scope of Work



Single-Mode Mid-Infrared Fibres

- **Chalcogenide Fibres** (NRL)
  - A. Ksendzov et al., "Characterization of mid-infrared single mode fibers as modal filters," Applied Optics 46, 7957-7962 (2007)
  - Transmission losses 8 dB/m
  - Suppression of 1000 for higher order modes
  - Useable to ~11 microns



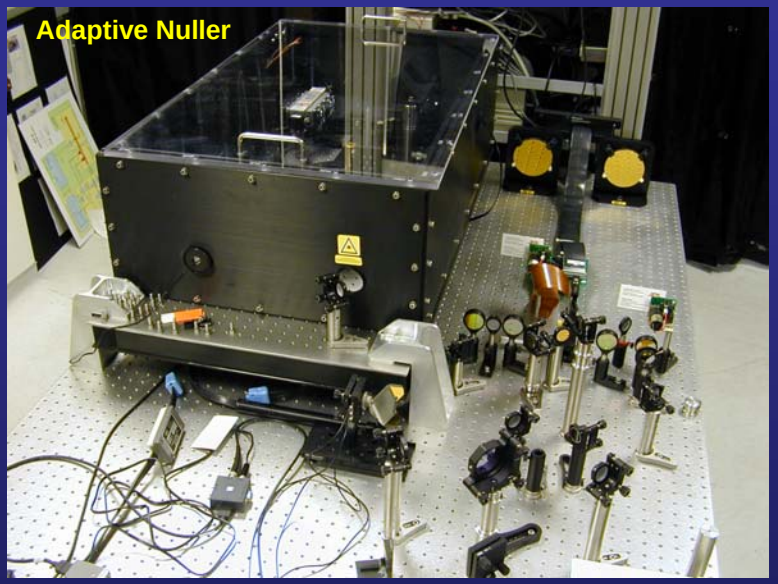
Example Chalcogenide Fibres, produced on contract by the Naval Research Laboratory

- **Silver-Halide Fibres** (Tel Aviv Univ)
  - A. Ksendzov et al. "Model filtering in mid-infrared using single-mode silver halide fibers," Applied Optics, in preparation.
  - Transmission losses 12 dB/m
  - Suppression of 16000 possible with a 10-20 cm fibre, with aperturing the output.
  - Useable to ~18 microns (?)

http://planetquest.jpl.nasa.gov/TPF-I/spatialFilters.cfm

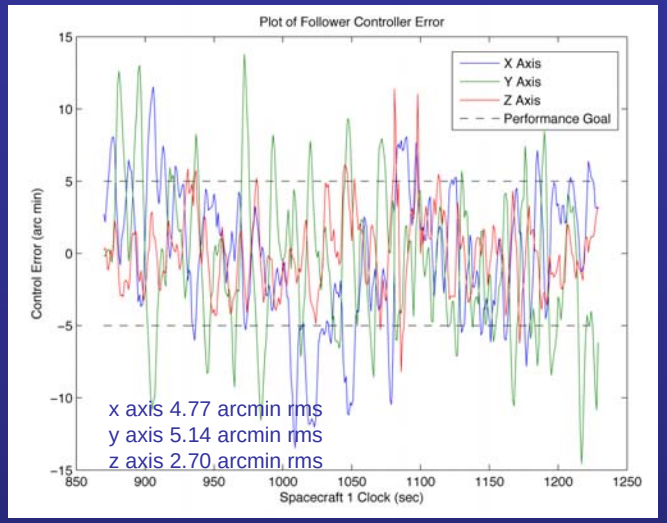
TPF-I Milestone #1: Adaptive Nuller

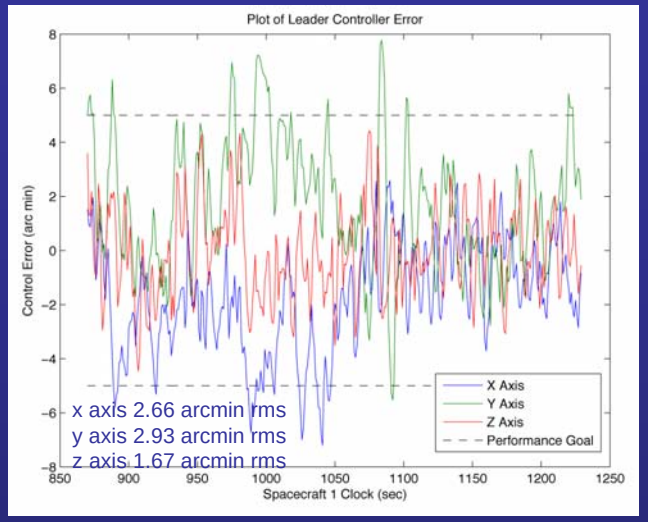
- **Adaptive Nuller**
  - **TPF-I Milestone #1** completed. The milestone report for the phase and intensity demonstration was approved and signed by NASA HQ, 24 July 2007
    - Demonstrated 0.09% intensity compensation and 4.4 nm phase compensation
  - Demonstrated 1.2×10^{-5} mean null depth with a 32% bandwidth, only a factor of 1.2 from the flight requirements
  - TPF-I Milestone #3 whitepaper for broadband nulling demonstration signed 10 October 2007

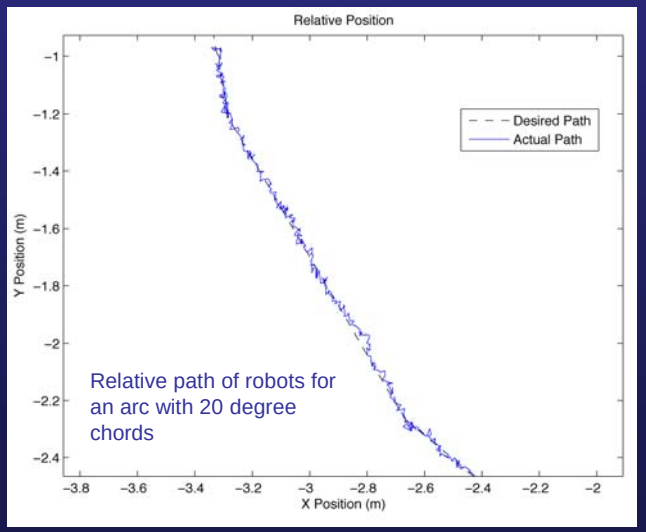


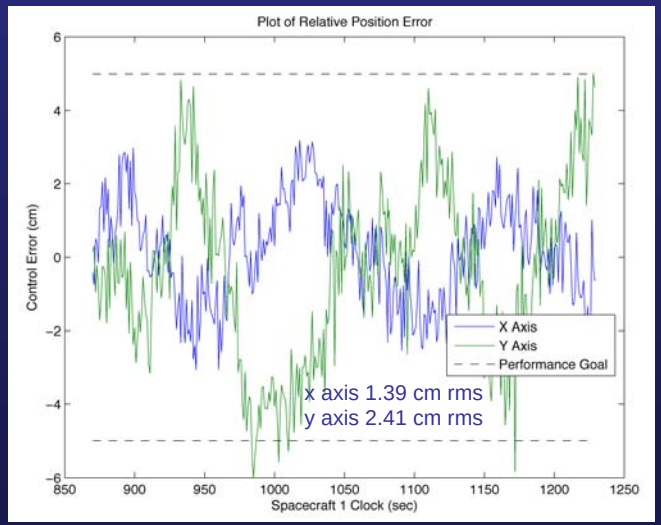
TPF-I Milestone #1 Completed
Amplitude & phase compensation
Final report signed 24 July 2007

TPF-I Milestone #2: Formation Control Testbed









Example Milestone Data: Rotation maneuver with 20 degree chord segments

TPF-I Milestone #2 experiments for the formation precision performance maneuver were completed 30 September 2007

Goal:

Per axis translation control < 5 cm rms

Per axis rotation control < 6.7 arcmin rms

Demonstrated with arcs having 20 and 40 degree chords. Experiments repeated three times, spaced at least two days apart.

Milestone Report Published for 16 January 2008

TPF-I Technology Summary & Conclusion

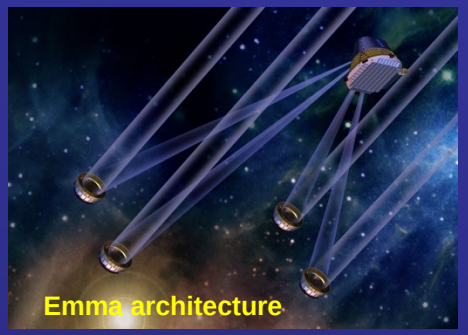
Interferometry Technology Goals

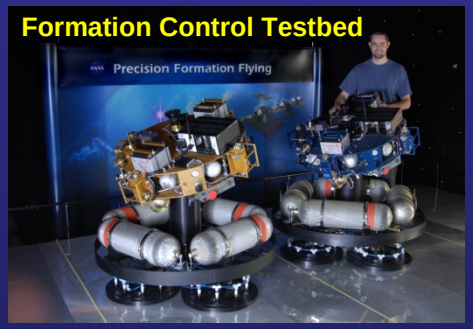
- Demonstrate 10^{-5} broadband mid-IR starlight suppression
- Demonstrate fault-tolerant algorithms for formation flying in a ground-based lab and at the ISS

Highlights

- Formation Flying Testbed demonstrates precision performance
- *Laser* nulling exceeding flight requirement
  - 10^{-6} achieved in the lab
- *Broadband* nulling now within a factor of 1.2 of flight requirement:
  - Adaptive Nuller Testbed demonstrates (5 nm phase and 0.2% intensity compensation)
  - Adaptive Nuller Testbed achieves a 1.2×10^{-5} null with a 32% bandwidth
  - Current performance would add only 5% to the integration time needed to detect Earth at 15 pc
- *Instability noise breakthrough* means that the null depth requirement is now only 10^{-5}
- NASA and ESA concepts are identical
  - Work with the same design
  - Performance estimates closely agree

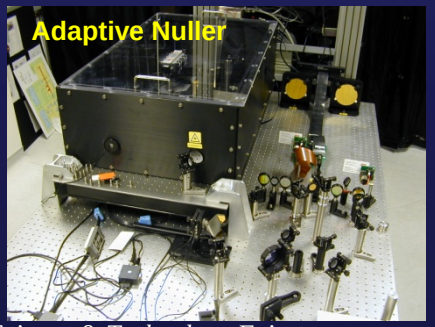
'Emma' geometry reduces complexity & increases sky coverage





Precision performance milestone demonstrated in September 2007

Simulated earth extracted at 5×10^{-7} contrast ratio



Record broadband mid-IR nulls: 1.2×10^{-5} null @ 32% BW

Acknowledgments

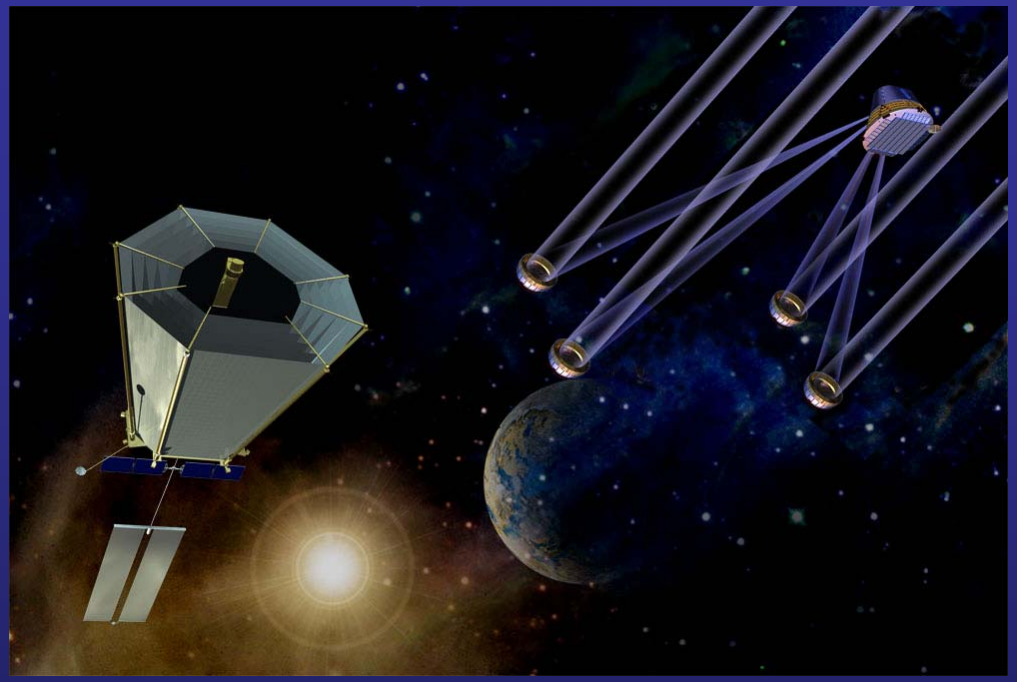
- This work was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

Backup Slides

Terrestrial Planet Finder Overview

Salient Features

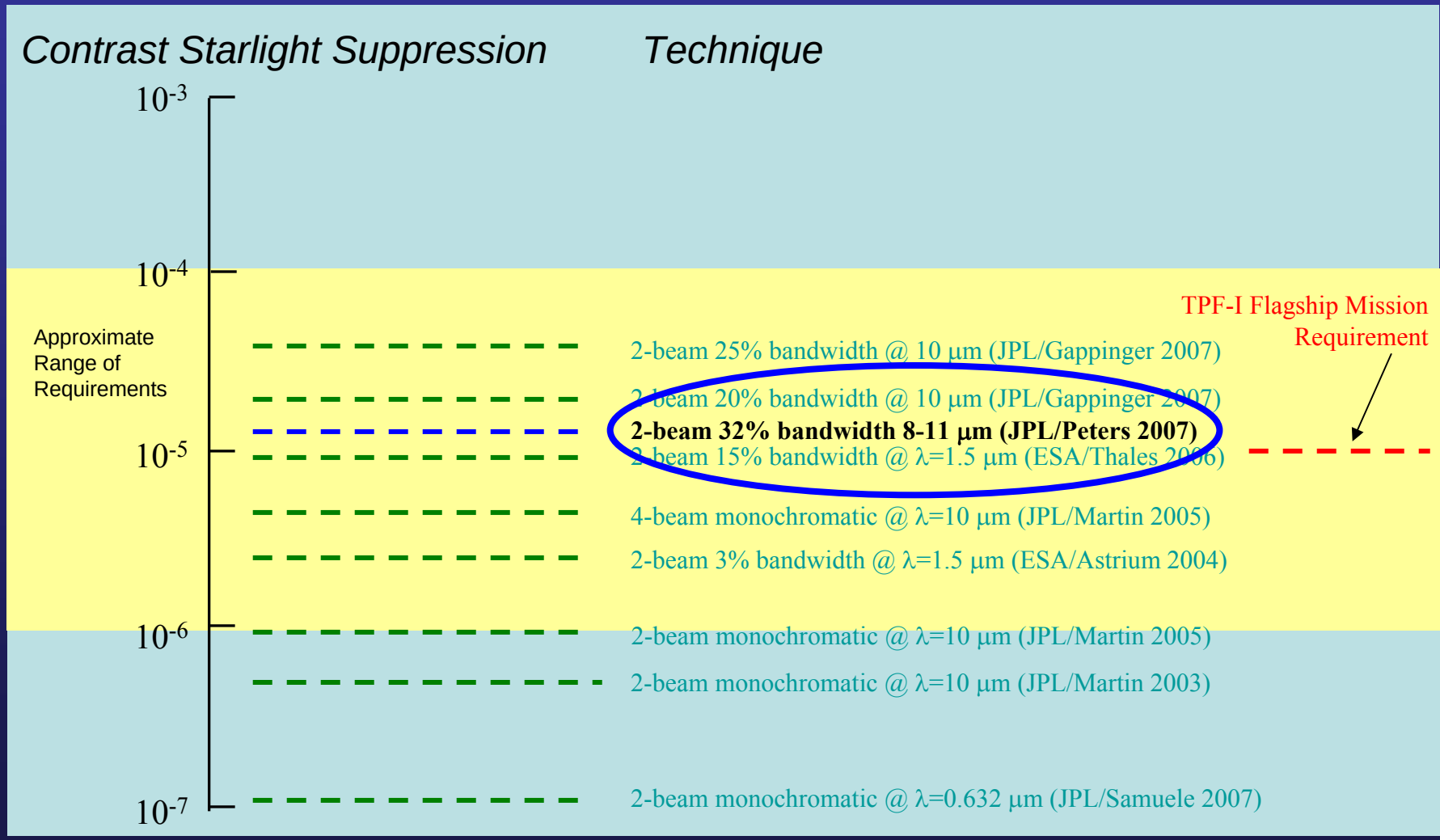
- Visible-NIR Coronagraph and Formation Flying Mid-IR nulling Interferometer
- Starlight suppression to 10^{-10} (vis) and 10^{-5} (mid-IR)
- Heavy launch vehicles
- L2 baseline orbit
- 5 year mission life (10 year goal)
- Potential collaboration with European Space Agency DARWIN Mission on the Formation Flying Interferometer



Science Goals

- Detect as many as possible Earth-like planets in the “habitable zone” of nearby stars via their reflected light or thermal emission
- Characterize physical properties of detected Earth-like planets (size, orbital parameters, albedo, presence of atmosphere) and make low resolution spectral observations looking for evidence of a *habitable* planet and bio-markers such as O_2, O_3, CO_2, CH_4 and H_2O
- Detect and characterize the components of nearby planetary systems including disks, terrestrial planets, giant planets and multiple planet systems
- Perform general astrophysics investigations as capability and time permit

State of the Art in Mid-Infrared Nulling



Properties of a TPF-I Observatory

Table 1. Illustrative Properties of a TPF-I Observatory Concept

Parameter	4-Telescope Chopped X-Array Emma Design
Collectors	Four 2-m diameter spherical mirrors, diffraction limited at 2 μm operating at 50 K
Array shape	6:1 rectangular array
Array size	400 × 67 m to 120 × 20 m
Wavelength range	6–20 μm
Inner working angle	13–43 mas (at 10 μm, scaling with array size)
Angular resolution	2.4 mas to 8.2 mas (at 10 μm, scaling with array size)
Field-of-view	1 arcsec at 10 μm
Null depth	10^{-5} at 10 μm (not including stellar size leakage)
Spectral resolution Δλ/λ	25 (for planets); 100 for general astrophysics
Sensitivity	0.3 μJy at 12 μm in 14 hours (5σ)
Target Stars	153 (F, G, K, and M main-sequence stars)
Detectable Earths	130 (2 year mission time, 1 Earth per star)
Exozodiacal emission	Less than 10 times our solar system
Biomarkers	CO_2, O_3, H_2O, CH_4
Field of regard	Instantaneous 45° to 85° from anti-Sun direction, 99.6% of full sky over one year.
Orbit	L2 Halo orbit
Mission duration	5 years baseline with a goal of 10 years
Launch vehicle	Ariane 5 ECA or equivalent